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COMMUNICATIONS

Photoluminescence of $InAs_{1-x}Sb_x$/AlSb single quantum wells: Transition from type-II to type-I band alignment

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Infrared photoluminescence has been used to study the band-gap energy of $InAs_{1-x}Sb_x$ digital superlattices and band alignment of $InAs_{1-x}Sb_x$/AlSb quantum wells at 5 K. It is found that the $InAs_{1-x}Sb_x$ digital alloys have a smaller effective band gap than $InAs_{1-x}Sb_x$ random alloys. In addition, the valence band offset between type-II InAs/AlSb is determined to be 130 meV. This number reduces as the Sb mole fraction in $InAs_{1-x}Sb_x$ is increased, and the alignment between $InAs_{1-x}Sb_x$/AlSb becomes type I when $x>0.15$. © *2000 American Institute of Physics.* [S0021-8979(00)03911-6]

High-frequency operation and low power consumption are key issues for communication devices. One way to improve device performance is through device scaling. However, before device scaling inevitably reaches its fabrication and physical limitations, new material systems and/or new device structures should be explored. It is crucial for microwave applications to have a transistor channel with high conductivity and high electron saturation velocity.[1] For these reasons, the channel material for field-effect transistors (FET) has been shifting from GaAs toward $In_yGa_{1-y}As$ with a higher and higher In mole fraction. As a result, the barrier material, which requires strong carrier confinement and lattice match, has been changed from $Al_yGa_{1-y}As$ to $In_yAl_{1-y}As$ and then to AlSb for InAs channels. Recently, low-voltage, high-speed performance has been demonstrated for InAs/AlSb high-electron-mobility transistors (HEMTs) owing to the excellent intrinsic electron properties in InAs and the large conduction band offset between InAs and AlSb. However, the lack of hole confinement for the staggered, type-II band alignment in InAs/AlSb HEMTs impedes the projected progress. Although a few remedies have been shown effective,[1,2] a type-I alignment between the channel and barrier materials is still preferred.[3]

Recently, it has been demonstrated that the ternary barrier, $AlAs_ySb_{1-y}$ exhibits a type-I alignment with InAs channels.[4] In this letter, we report the investigation of a ternary semiconductor for channel material, $InAs_{1-x}Sb_x$, and its band alignment with AlSb barrier. Since the electron mobility and saturation velocity for InSb are even superior to InAs, an addition of Sb in the channel has the potential to further improve the HEMT's performance. In this work, the $InAs_{1-x}Sb_x$ was grown as $(InAs)_n(InSb)_1$ digital superlattices[5] by modulation molecular-beam epitaxy (MMBE).[6] We found that $InAs_{1-x}Sb_x$ grown by this technique has a smaller effective band gap than $InAs_{1-x}Sb_x$ random alloys. This band-gap reduction is attributed to the InAs/InSb lattice ordering in the context of the x-ray diffraction measurements and the tight binding calculation.[7] In addition, we use infrared photoluminescence (PL)[8] to demonstrate the desired type-I alignment for the lattice closely matched $InAs_{0.8}Sb_{0.2}$/AlSb system.

Compared to dual-cation ternary semiconductors, the composition ratio in dual-anion alloys is more difficult to control with MBE growth due to the nonunity sticking coefficient for group-V elements. One approach to composition control is to utilize MMBE. This versatile technique provides enough accuracy and reproducibility, and has been proven to improve the crystalline quality of $AlAs_{1-y}Sb_y$.[6] Owing to the small band gap, $InAs_{1-x}Sb_x$ random alloys have been investigated for infrared detectors[9] and infrared lasers,[10] and have been grown by different methods including MBE.[11,12] In contrast, $InAs_{1-x}Sb_x$ digital alloys were grown by MMBE in this work as described in Ref. 5, and characterized by high-resolution x-ray diffraction and infrared PL. Due to the large lattice mismatch between the binary end points, InAs (6.0584 Å) and InSb (6.4794 Å), the InSb is kept at one monolayer each period, and the composition is adjusted by the duration of InAs growth. All samples were grown on GaAs substrates with 40–51 periods of $(InAs)_n(InSb)_1$, where n is the number of InAs monolayers. Three of the samples ($x=5\%$, 11%, and 15%) have a 1-μm InAs buffer layer, while two of them ($x=18\%$, and 22%) have a 1-μm AlSb buffer. The determination of x is based on x-ray measurements. For example, a determination of a relaxed lattice constant of 6.1210 Å implies $x=15\%$. This particular epi film has the largest lattice mismatch to the buffer, i.e., 1.0%,

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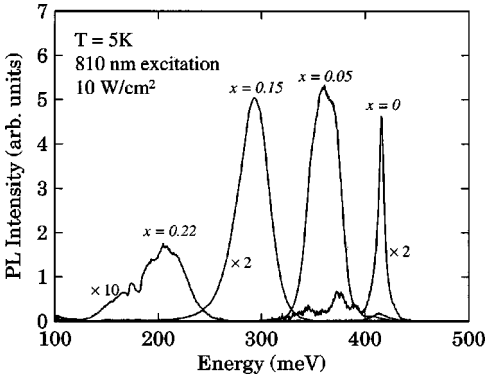


FIG. 1. Normalized photoluminescence spectra for four epitaxial films.

among all of the samples in this work. Based on high-resolution x-ray analysis, the in-plane and vertical lattice constants of a 860 Å thick $InAs_{0.85}Sb_{0.15}$ digital alloy are found to be 6.0834 and 6.1548 Å, respectively, implying a strain factor of 0.60.

Figure 1 exhibits the normalized PL spectra at 5 K for four epitaxial films, $x=0\%$ (4-μm InAs on a GaAs substrate), 5%, 11%, and 22%, where the excitation power is 10 W/cm^2 at 810 nm. As we can see, when x is increased, the peak energy decreases and the linewidth increases; the full width at half maximum is 6.5, 34.5, 35.1, and 62.4 meV, respectively. For the epitaxial film with $x=0$, several apparently impurity related lines are observed. In contrast, for samples with $x=11\%$, the only distinguishable line other than the main peak is at 414 meV, which is from the InAs buffer layer. The absorption features around 180 meV are due to residual mounting grease on the sample surface. Figure 2 summarizes the PL peak energies at 5 K, where the PL for $x=1$ was performed on a 4-μm-thick InSb epitaxial film grown by MBE on an InSb substrate. The solid curve is the experimental band-gap energy for random alloys obtained by Fang *et al.*[13] Our binary endpoints ($x=0$ and 1) are consistent with the solid curve. However, the bandgap for digital alloys falls below that of random alloys. For example, the band gap for digital $InAs_{0.78}Sb_{0.22}$ is 65 meV smaller. A band-gap reduction for MBE-grown $InAs_{1-x}Sb_x$ random alloys has been reported, and is attributed to strain effects and natural phase separation.[11,12]

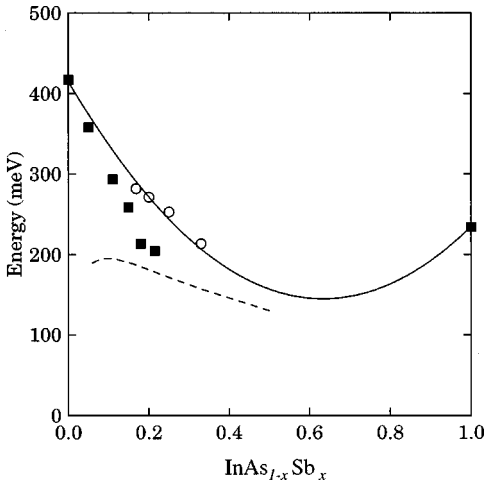
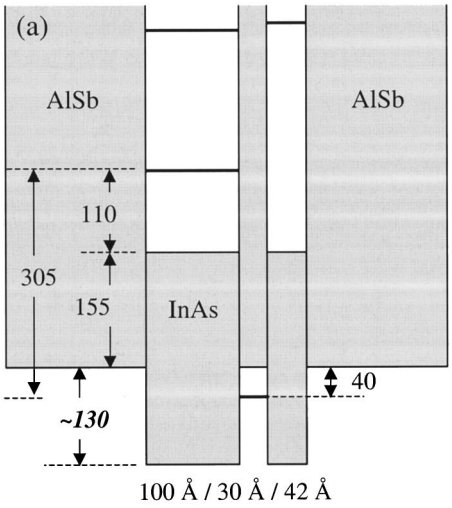


FIG. 2. Energy band gap of $InAs_{1-x}Sb_x$ as a function of Sb composition. Solid squares and open circles are 5 K photoluminescence peak energies for digital $InAs_{1-x}Sb_x$ alloys, and for $InAs_{1-x}Sb_x$/AlSb single quantum wells, respectively. Solid and dashed curves are from Refs. 13 and 7, respectively.

The periodicity of our digital alloys is evident from the existence of satellite peaks in the single-crystal x-ray diffraction.[5] We have also carried out a tight-binding calculation for $(InAs)_n(InSb)_1$ superlattices assuming a relaxed (i.e., free-standing) lattice constant and a valence band offset of 0.5 eV between unstrained InAs and InSb. The calculated effective band gap is plotted as the dashed curve in Fig. 2. It is clear that, although our data lie between the solid and the dashed curves, they follow more closely the solid one. This suggests that our epi films have essentially a random alloy nature but with some group-V modulation.

With the knowledge we gained from the digital superlattices, we grew several $InAs_{1-x}Sb_x$ single quantum wells sandwiched by AlSb in order to examine the band alignment between the AlSb and $InAs_{1-x}Sb_x$. More specifically, we will first determine the band offset between InAs and AlSb, and then identify the minimum Sb composition required to form the type-I alignment with AlSb. Due to the type-II alignment, i.e., lack of hole confinement, the InAs single quantum well is almost nonluminous.[14] We amended the structure with an additional thin InAs quantum well so the hole can be confined in the AlSb layer, as depicted in the schematic band diagram of Fig. 3(a). Luminescence that peaks at 305 meV has been detected on this sample, originating from the recombination of electrons in the 100 Å InAs quantum well and holes in the 30 Å AlSb. The subband energies are calculated, respectively, to be 110 and 40 meV, where the nonparabolicity and wave function penetration effects[15] are considered. It is known that the InAs quantum well is fully strained to AlSb lattice (6.1355 Å) for a well thickness less than 200 Å.[16] As a result of this 1.3% biaxial tension, the InAs band gap is reduced from 420 to 287 meV at 0 K.[17] With the simple model indicated in Fig. 3(a), the valence band offset between the AlSb and InAs is determined to be ~130 meV. This is smaller than, but consistent with the value of 160 meV obtained from photoemission experiments,[18] and the value of 190 meV calculated by first-principle local density functional theory.[19]

The addition of Sb in InAs is expected to reduce the valence band offset since the valence band maximum of the unstrained InSb is close to the conduction band minimum of the unstrained InAs. Moreover, with 18% Sb, the $InAs_{1-x}Sb_x$ well is lattice matched to AlSb, which is more favorable for device applications. We first investigated a 153 Å $InAs_{0.80}Sb_{0.20}$/AlSb single quantum well, grown as a digital superlattice with 10 periods of $(InAs)_4(InSb)_1$. Its schematic diagram is illustrated in Fig. 3(b). We observed a PL signal, whose integrated intensity is only three times smaller than the 872 Å ''bulk'' $InAs_{0.78}Sb_{0.22}$, in contrast to nonluminous InAs single quantum wells. This is the signature of type-I band alignment. The peak energy is 272 meV for the SQW as opposed to 205 meV for ''bulk'' $InAs_{0.78}Sb_{0.22}$. This implies that the confinement energy is 67 meV,[15,17] which is consistent with the expectation of small electron



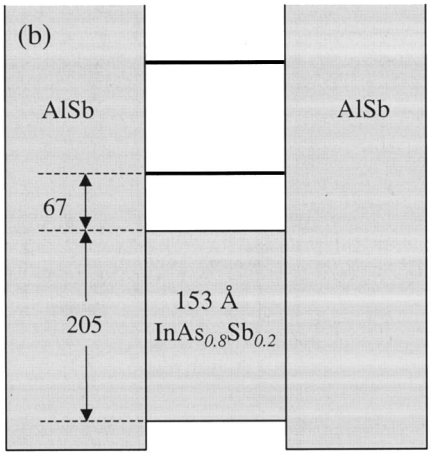


FIG. 3. Schematic band edge diagrams of (a) InAs/AlSb quantum well with an InAs subchannel, and (b) $InAs_{0.80}Sb_{0.20}$/AlSb quantum well, where the energy is in units of meV. The first few subbands in each quantum well are also indicated.

mass for $InAs_{1-x}Sb_x$. The peak energies for several 150 Å SQWs are included in Fig. 2 as open circles. Since the Sb composition in $InAs_{1-x}Sb_x$ SQW cannot be obtained by x-ray diffraction, we designated the x value based on $x=1/(1+n)$. Note the coincidence that open circles lie along the solid curve. This is because the band-gap reduction due to ordering is compensated by the subband energy, where both are in the order of 65 meV. We observed PL for $n=2$, 3, 4, and 5, i.e., $x=33\%$, 25%, 20%, and 17%. However, as with InAs/AlSb SQW, we do not detect PL for $n=6$ and 7, i.e., $x=14\%$ and 12.5%, respectively. As a result, we concluded that the transition from type-II to type-I band alignment occurs around $x=15\%$.

In summary, we have systematically studied the $(InAs)_n(InSb)_1$ digital superlattices. Based on the PL experiment at 5 K, the effective band gap of digital $InAs_{1-x}Sb_x$ alloys is smaller than the random $InAs_{1-x}Sb_x$ alloys. This band-gap reduction, which is attributed to the ordering effect, gets bigger as x is increased. In addition, we have also investigated the valence band offset between $InAs_{1-x}Sb_x$ quantum wells and AlSb barriers. This offset is determined to be 130 meV for $x=0$, and gets smaller as x is increased. Most importantly, it is found that when $x>15\%$, the $InAs_{1-x}Sb_x$/AlSb quantum well forms type-I band alignment, which is a desirable characteristic for FET devices.

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